Design of Lowpass Filter and Lowpass-Highpass Diplexer with LTCC Technology

Chunxia Zhou [1*], Yongxin Guo [2], and Wen Wu [1]

[1] Ministerial Key Laboratory of JGMT
Nanjing University of Science and Technology, Nanjing, 210094, China
zhouchx1010@gmail.com*, wuwen@njust.edu.cn

[2] Department of Electrical and Computer Engineering
National University of Singapore, Singapore 117583, Singapore
yongxin.guo@nus.edu.sg

Abstract ─ A compact lowpass filter (LPF) and a lowpass-highpass diplexer (LPD) with both sharp roll-off and wide stopband is presented in this paper. The proposed LPF is realized by cascading modified hairpin unit consisting of one U-shape stripline and one pair of offset-coupled striplines with multilayer low-temperature co-fired ceramic (LTCC) technology. The LPD is realized by shunting a lowpass filter and a highpass filter at a common junction to achieve all-reject in one port. Good agreement can be achieved by the simulated and measured results.

Index Terms ─ Coupled lines, Low-Temperature Co-fired Ceramic (LTCC), Lowpass filter (LPF), Lowpass-Highpass Diplexer (LPD).

I. INTRODUCTION

Compact, low cost, and highly integrated passive and active components are highly demanded by wireless-device manufacturers. The low temperature cofired ceramic (LTCC) technology, as one of the most promising methods, has been extensively utilized in recent years. LTCC offers layout flexibility and three-dimensional (3D) integration capability to produce embedded passive components, for example, filters [1, 2] and antennas [3], phase shift [4] and coupler [5]. The lowpass filter (LPF) is one of key passive components that are widely used in wireless systems to filter out unwanted signals. There are several conventional methods to design LPFs such as using shunt stubs, high-low impedance transmission lines, or cascading multiple resonators [6, 7]. However, it is quite hard to achieve LPFs with sharp attenuation skirt and compact size simultaneously. To overcome this difficulty, modified hairpin resonators have been widely adopted due to its compactness and flexibility. Various types of miniaturized and performance-improved LPFs have been studied based on hairpin resonators [8-14]. Elliptic-function LPFs with a wide stopband are presented in [8] by cascading microstrip stepped-impedance hairpin resonators. In [9], stopband-extended LPFs were realized by centrally tap-connecting the microstrip coupled-line hairpin resonator. In [10], a LPF with wide stopband was designed by cascading microstrip coupled-line hairpin resonator, semi-circle defected ground structures and semi-circle stepped-impedance shunt stubs. Stepped-impedance hairpin resonators with an interdigital structure [11, 12], shunt open-stubs [13], and radial stubs [14] were used for designing LPFs with sharp and expanded stopband.

In this paper, a compact LTCC LPF with sharp roll-off and wide stop-band is presented by cascading modified hairpin units. The unit consists of one U-shape stripline and one pair of offset-coupled striplines with multilayer LTCC technology. Measured results indicate that the designed filter has an ultra-wide stopband rejection better than 10 dB up to 20 GHz and a sharp roll-off of 81 dB/GHz. Furthermore, a lowpass-highpass diplexer (LHD) is presented to achieve all-reject in one port. It is realized by shunting a lowpass filter and a highpass filter at a common junction.

II. LOWPASS FILTER DESIGN

Figure 1 (a) shows the circuit schematic of the lowpass filter. It is realized by four sections of modified hairpin units. Each unit consists of one transmission line with electric length of θ_{Li} and impedance of Z_i, and one pair of coupled lines with electric length of θ_{Ci} and even- and odd-mode impedances of Z_{ei} and Z_{oi} (i=1, 2, 3, 4). Figure 1 (b) gives the corresponding equivalent circuit, which is the prototype of elliptic-function LPF. The elliptic-function LPF is designed with cutoff frequency of f=4.5 GHz, passband ripple of 0.03 and attenuation in the stopband of -60 dB. With the element-value tables and frequency and element transformations [15], L-C

Submitted On: September 30, 2015
Accepted On: May 3, 2016

values of the 9-order elliptic-function LPF can be calculated as follows: L_1=2.611 (nH), L_2=1.812 (nH), L_3=1.499 (nH), L_4=1.878 (nH), C_{g1}=0.097 (PF), C_{g2}=0.584 (PF), C_{g3}=0.803 (PF), C_{g4}=0.385 (PF), C_{p1}=0.686 (PF), C_{p2}=0.415 (PF), C_{p3}=0.399 (PF) and C_{p4}=0.497 (PF). Then, the relationship between the parameters in Fig. 1 (a) and those in Fig. 1 (b) can be obtained [8]:

$$L_i = Z_i \sin(\theta_{Li}) / \omega \quad \text{(H)}, \tag{1}$$

$$C_{gi} = (Z_{ei} - Z_{oi}) / (2\omega Z_{ei} Z_{oi} \cot(\theta_{Ci})) \quad \text{(F)}, \tag{2}$$

$$C_{pi} = 1 / (\omega Z_{ei} \cot(\theta_{Ci})) \quad \text{(F)}, \tag{3}$$

$(i = 1,2,3,4)$.

By comparing Equations (2) and (3),we can get:

$$Z_{ei} / Z_{oi} = (2C_{gi} + C_{pi}) / C_{pi}. \tag{4}$$

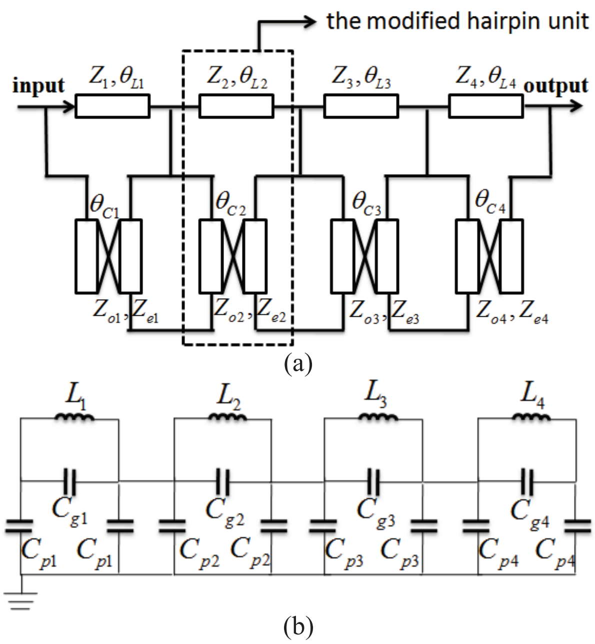

Fig. 1. Diagram of proposed LPF. (a) Circuit schematic and (b) corresponding equivalent circuit.

III. LOWPASS-HIGHPASS DIPLEXER DESIGN

Figure 2 shows the circuit schematic of the proposed LHD. It is realized by shunting a lowpass filter and a highpass filter at a common junction. It consists of five striplines with electric length of θ_i and impedance of Z_i (i=1,2,3,4,7), and four coupled lines with electric length of θ_i and even- and odd-mode impedance of Z_{ei} and Z_{oi} (i=5,6,8,9). To minimize reflections at the input port 1, the complex input admittances $Y_{in,LP}$ and $Y_{in,HP}$ of the two filters should satisfy at all frequencies the equation:

$$Y_{in} = Y_{in,LP} + Y_{in,HP} = Y_0. \tag{5}$$

This condition can be split into the following two conditions:

$$\begin{aligned} \mathrm{Re}(Y_{in,LP}) + \mathrm{Re}(Y_{in,HP}) &= Y_0 \\ \mathrm{Im}(Y_{in,LP}) + \mathrm{Im}(Y_{in,HP}) &= 0 \end{aligned}. \tag{6}$$

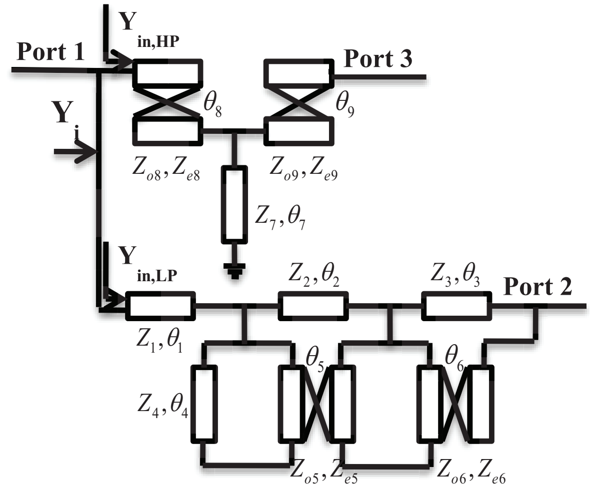

Fig. 2. Circuit schematic of the proposed LHD.

IV. FILTER AND DIPLEXER IMPLEMENTATION IN LTCC TECHNOLOGY

The filter and diplexer are designed in a 10-layer LTCC substrate, with the relative permittivity of 5.9, loss tangent of tanδ=0.0015, and thickness of each substrate layer of 96 µm. There are 11 metal layers from top to bottom. The 3D configuration of the proposed LPF is illustrated in Fig. 3. The configuration is build up according to the basic circuit shown in Fig. 1 (a). The sections of four transmission lines are realized by U-shape striplines in metal layer 5, layer 6 and layer 8, with width of 0.2 mm. According to Equation (1), we can get $\theta_{L1}=90^0$, $\theta_{L2}=49.4^0$, $\theta_{L3}=38.9^0$ and $\theta_{L4}=51.9^0$. The sections of four pairs of coupled lines are realized by offset-coupled striplines with width of 0.53 mm. Then adjusting the relatively positions of the offset-coupled striplines to satisfying Equation (4), we can get each Z_{ei}, Z_{oi}, and θ_{Ci} (i=1,2,3,4). With trial-and-error operations, the first pair of coupled lines is determined in layers 2 and 8, the second in layers 7 and 8, the third in layers in 6 and 7 and the forth in layers 4 and 6. Furthermore, Z_{e1}=28.2 Ω, Z_{o1}=22.1 Ω, $\theta_{C1}=25.8^0$, Z_{e2}=50.6 Ω, Z_{o2}=13.2 Ω, $\theta_{C2}=27.6^0$, Z_{e3}=55 Ω, Z_{o3}=10.9 Ω, $\theta_{C3}=28.7^0$, Z_{e4}=48 Ω, Z_{o4}=18.1 Ω, $\theta_{C4}=29.6^0$. After optimization using Ansoft HFSS, we can get that the lengths of the four striplines corresponding to θ_{L1}, θ_{L2}, θ_{L3} and θ_{L4} are 5.45 mm, 4.36 mm, 3.13 mm and 5.2 mm respectively. The lengths of the coupled striplines corresponding to θ_{C1}, θ_{C2}, θ_{C3} and θ_{C4} are 1.8 mm, 2 mm, 2.2 mm and 2.24 mm respectively. The designed parameters of the LPF are summarized in Table 1. The S-parameters in both the simulated and the measured results are shown in Fig. 4. The photo of the filter prototype is shown in Fig. 5. Its overall size is only

$4.54\times3.37\times0.96$ mm^3. For comparison, Table 2 summarizes the performances of some published lowpass filters. As can be seen from the table, our proposed filter has the properties of sharp roll-off, ultra-wide stopband, and compact size simultaneously.

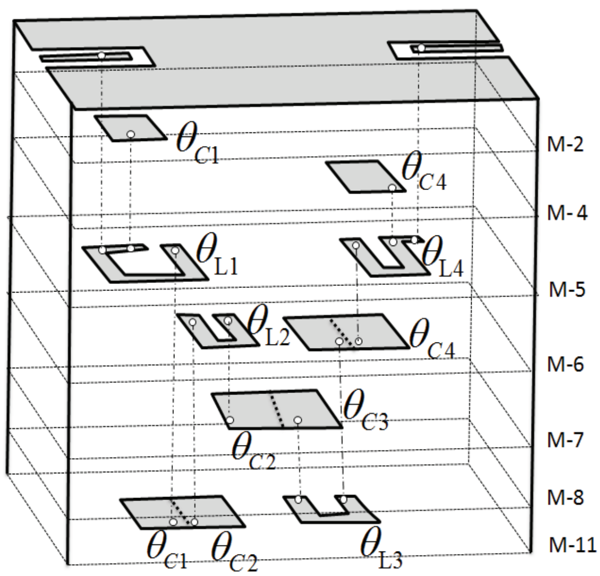

Fig. 3. 3D configuration of the proposed LPF.

Table 1: The designed parameters of the LPF

i	1	2	3	4
θ_{Li}	90^0	49.4^0	38.9^0	51.9^0
θ_{Ci}	25.8^0	27.6^0	28.7^0	29.6^0
Z_{ei} (Ω)	28.2	50.6	55	48
Z_{oi} (Ω)	22.1	13.2	10.9	18.1
L_{Li} (mm)	5.45	4.36	3.13	5.2
L_{Ci} (mm)	1.8	2	2.2	2.24

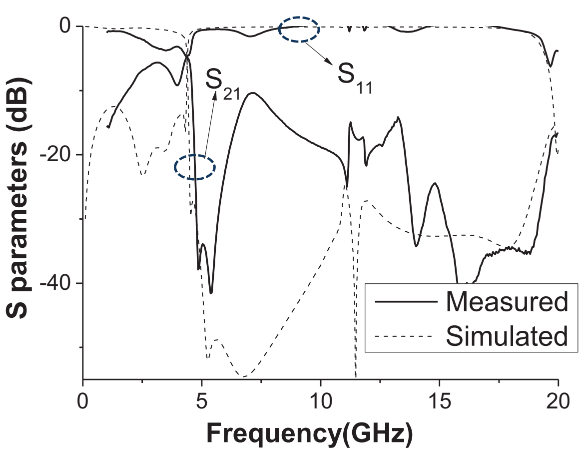

Fig. 4. Simulated and measured results of the LPF.

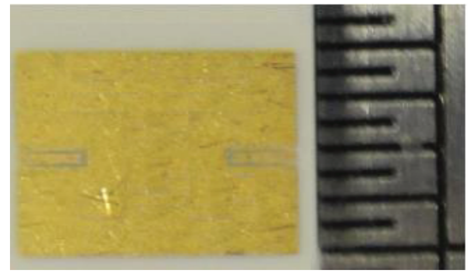

Fig. 5. Photo of the lowpass filter prototype.

Table 2: Performance comparisons among published filters and the proposed one

Ref.	Roll Off (dB/GHz)	Stopband Up to (GHz)	Circuit Size (λ_g*λ_g)
[8]	37	4.8	0.09*0.35
[9]	45	15	0.23*0.27
[10]	74	6	0.11*0.10
[11]	95	9	0.10*0.21
[12]	28	12	0.08*0.08
[13]	43.2	12	0.39*0.83
This work	81	20	0.14*0.11

The 3D configuration of the proposed LHD is illustrated in Fig. 6. The configuration is build up according to the basic circuit shown in Fig. 2. The sections of five transmission lines are realized by microstrip line in the top metal (θ_1) with width of 0.2 mm, U-shape striplines in metal layer 6 (θ_2) and layer 4 (θ_3) with width of 0.2 mm, stripline in layer 4 (θ_4) with width of 0.6 mm and L-shape stripline in metal layer 6 (θ_5) with width of 0.2 mm. The sections of four pairs of coupled lines are realized by offset-coupled striplines in layers 4 and 7 (θ_5) with width of 0.6 mm, the second in layers 2 and 7 (θ_6) with width of 0.6 mm, the third in layers in 5 and 6 (θ_8) with width of 0.2 mm and the forth in layers 4 and 6 (θ_9) with width of 0.6 mm. To satisfying Equation (5), the design parameters are determined as follows: θ_1=43^0, θ_2=47^0, θ_3=46^0, θ_4=29^0, θ_5=37^0, θ_6=20^0, θ_7=47^0, θ_8=25^0 and θ_9=10^0.

After optimization using Ansoft HFSS, we can get that the lengths of one microstrip line and four striplines corresponding to θ_1, θ_2, θ_3, θ_4 and θ_7 are 3.3 mm, 3.6 mm, 3.5 mm, 2.2 mm and 1.6 mm respectively. The lengths of the coupled striplines corresponding to θ_5, θ_6, θ_8 and θ_9 are 2.7 mm, 1.5 mm, 1.9 mm and 0.5 mm respectively. The designed parameters of the LHD are summarized in Table 3. Both the simulated and the measured results are shown in Fig. 7. The photo of the diplexer prototype is shown in Fig. 8. Its overall size is only $5.8\times5.3\times0.96$ mm^3. For comparison, Table 4 summarizes the performances of some published diplexers.

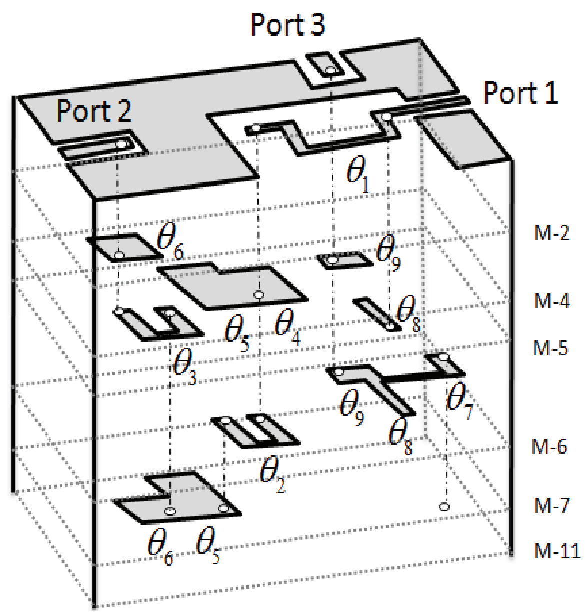

Fig. 6. 3D configuration of the proposed LHD.

Table 3: The designed parameters of the LHD

i	1	2	3	4	5	6	7	8	9
θ_i	43^0	47^0	46^0	29^0	37^0	20^0	47^0	25^0	10^0
L_i (mm)	3.3	3.6	3.5	2.2	2.7	1.5	1.6	1.9	0.5

Table 4: Performance of diplexers

Ref.	Type	f_c (GHz)	Size (λ_g*λ_g)
[15]	Lowpass-Bandpass	1.5	0.80*0.41
[16]	Lowpass-Highpass	0.92	0.43*0.20
This work	Lowpass-Highpass	4.5	0.18*0.16

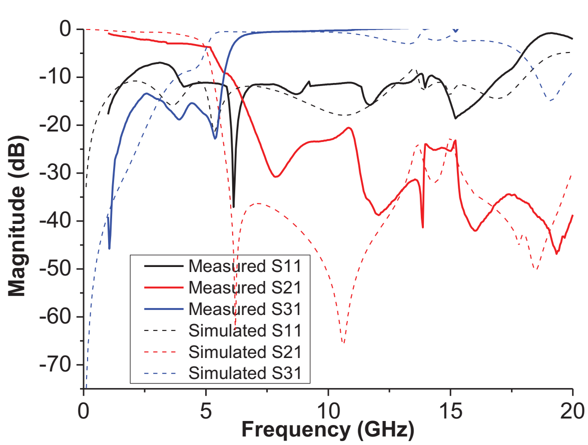

Fig.7. Simulated and measured results of the LHD.

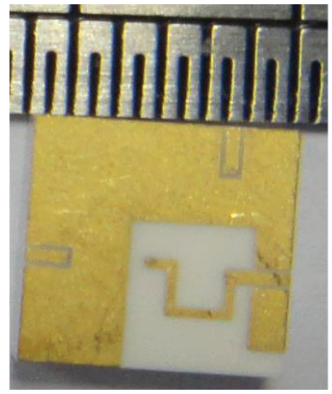

Fig. 8. Photo of the lowpass diplexer prototype.

V. CONCLUSION

A compact LPF and LHD with sharp roll-off skirt and wide stopband are implemented in multilayer LTCC. The LPF is realized by cascading modified hairpin unit consisting of one U-shape stripline and one pair of offset-coupled striplines. The designed filter has an ultra-wide stopband rejection better than 10 dB up to 20 GHz and a sharp roll off of 81 dB/GHz. Furthermore, the size of the filter is only 4.54×3.37 mm^2. The LPD is realized by shunting a lowpass filter and a highpass filter at a common junction to achieve all-reject in one port. The size of the diplexer is 4.54×3.37 mm^2. The measured results are in good agreements with the simulation predictions.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation Committee of China (61401202).

REFERENCES

[1] L. K. Yeung and K. L. Wu, “A compact second-order LTCC bandpass filter with two finite transmission zeros,” *IEEE Trans. Microwave Theory & Tech*., vol. 51, no. 2, pp. 337-341, Feb. 2003.

[2] T. M. Shen, C. F. Chen, T. Y. Huang, et al., “Design of vertically stacked waveguide filters in LTCC,” *IEEE Trans. Microwave Theory & Tech*., vol. 55, no. 8, pp. 1771-1779, Aug. 2007.

[3] R. L. Li, G. DeJean, M. Maeng, et al., “Design of compact stacked-patch antennas in LTCC multilayer packaging modules for wireless applications,” *IEEE Trans. Compon., Packag., Manuf. Technol*., vol. 27, no. 4, pp. 581-589, Mar. 2013.

[4] A. Nafe and A. Shamim, “An integrable SIW phase shifter in a partially magnetized ferrite LTCC package,” *IEEE Trans. Microwave Theory & Tech*., vol. 63, no. 7, pp. 2264-2274, Jul. 2015.

[5] C. H. Tseng, "Compact LTCC rat-race couplers using multilayered phase-delay and phase-advance T-equivalent sections," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 33, no. 2, pp. 543-551, May 2010.

[6] I. S. Kim and S. W. Yun, "Compact LPF using asymmetrical microstrip step discontinuity for harmonic suppression," *Electron. Lett.*, vol. 41, no. 16, pp. 41-42, Aug. 2005.

[7] J. L. Li, S. W. Qu, and Q. Xue, "Compact microstrip lowpass filter with sharp roll-off and wide stop-band," *Electron. Lett*., vol. 45, no. 2, pp. 110-111, Jan. 2009.

[8] L. H. Hsieh and K. Chang, "Compact elliptic-function low-pass filters using microstrip stepped-impedance hairpin resonators," *IEEE Trans. Microw. Theory Tech*., vol. 51, no. 1, pp. 193-198, Jan. 2003.

[9] S. Luo, L. Zhu, and S. Sun, "Stopband-expanded low-pass filters using microstrip coupled-line hairpin units," *IEEE Microw. Wireless Compon. Lett*., vol. 18, no. 8, pp. 506-508, Aug. 2008.

[10] F. Wei, L. Chen, X. W. Shi, Q. L. Huang, and X. H. Wang, "Compact lowpass filter with wide stop-band using coupled-line hairpin unit," *Electron. Lett*., vol. 46 no. 1, pp. 88-90, Jan. 2010.

[11] L. Li, Z. F. Li, and J. F. Mao, "Compact lowpass filters with sharp and expanded stopband using stepped impedance hairpin units," *IEEE Microw. Wireless Compon. Lett*., vol. 20, no. 6, pp. 310-312, Jun. 2010.

[12] V. K. Velidi and S. Sanyal, "Sharp roll-off lowpass filter with wide stopband using stub-loaded coupled-line hairpin unit," *IEEE Microw. Wireless Compon. Lett*., vol. 21, no. 6, pp. 301-303, Jun. 2011.

[13] X. B. Wei, P. Wang, M. Q. Liu, and Y. Shi, "Compact wide-stopband lowpass filter using stepped impedance hairpin resonator with radial stubs," *Electron. Lett*., vol. 47, no. 15, pp. 862-863, Jul. 2011.

[14] M. Kufai and Z. Raida, "Lowpass filter with reduced fractal defected ground structure," *Electron. Lett*., vol. 49, no. 3, pp. 199-200, Jan. 2013

[15] P. H. Deng and J. T. Tsai, "Design of microstrip lowpass-bandpass diplexer," *IEEE Microw. Wireless Compon. Lett*., vol. 23, no. 7, pp. 332-334, Jul. 2013.

[16] M. Jung and B. W. Min, "Microstrip lowpass-highpass diplexer for a quadplexer application," *Microw. Opt. Technol. Lett*., vol. 56, no. 9, pp. 332-334, Jul. 2014.

[17] J. S. Hong and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*, New York: Wiley, 2001.

Chun-Xia Zhou (M'14) was born in Jiangsu Province, China, in 1985. She received the B.S. and Ph.D. degree in Electronic Engineering from Nankai University, Tianjin, China, in 2007 and 2012, respectively.

From September 2010 to February 2012, she was a joint Ph.D. student with the Department of Electrical and Computer Engineering, National University of Singapore (NUS), Singapore. From December 2012 to July 2012, she was a Research Fellow with Terahertz Science and Technology Research Center of China Academy of Engineering Physics, Chengdu, China. She is currently a Lecturer with the School of Electronic Engineering and Optoelectronic Technology, Nanjing University of Science and Technology, Nanjing, China. Her research interests include the design and optimization of microwave and millimeter-wave circuits, and microwave and millimeter-wave integrated circuits in CMOS technology.

Yong-Xin Guo (S'00–A'02–M'03–SM'05) received the Ph.D. degree from the City University of Hong Kong, Hong Kong, in 2001.

He is currently an Associate Professor with the Department of Electrical and Computer Engineering (ECE), National University of Singapore (NUS), Singapore, and Director of the Center for Microwave and Radio Frequency of the Department of ECE, NUS. Concurrently, he is a Senior Investigator with the National University of Singapore Research Institute (NUSRI), Suzhou, China, and Director of the Center of Advanced Microelectronic Devices, NUSRI. From September 2001 to January 2009, he was with the Institute for Infocomm Research, Singapore, as a Research Scientist. He has authored or co-authored 132 international journal papers and 150 international conference papers. His publications have been cited by others more than 1040 times (source: Scopus). He holds one Chinese Patent, one U.S. patent and four provisional U.S. patents. His current research interests include microstrip antennas for wireless communications, implantable/wearable antennas and body channel modeling for medical applications, wireless power and RF energy harvesting, microwave circuits, and monolithic microwave integrated circuit (MMIC) modeling and design.

Guo was the General Chair of the IEEE Microwave Theory and Techniques Society (MTT-S) International Microwave Workshop Series 2013 on "RF and Wireless Technologies for Biomedical and Healthcare Applications" (IMWS-Bio 2013), Singapore. He is an Associate Editor for IEEE Antennas and Wireless Propagation Letters (AWPL). He was a recipient of the Young Investigator Award 2009, National University of Singapore and the 2013 “Raj Mittra” Travel Grant Senior Researcher Award.

Wen Wu (SM’10) received the Ph.D. degree in Electromagnetic Field and Microwave Technology from Southeast University, Nanjing, China, in 1997.

He is currently a Professor with the School of Electronic Engineering and Optoelectronic Technology and an Associate Director with the Ministerial Key Laboratory of JGMT, Nanjing University of Science and Technology, Nanjing, China. He has authored and co-authored over 120 journal and conference papers. He has submitted five patent applications. His current research interests include microwave and millimeter-wave (mm-wave) theories and technologies, microwave and mm-wave detection, and multimode compound detection.

Wu was a six-time recipient of the Ministerial and Provincial-Level Science and Technology Award.